HYDROLOGIC MODELING SYSTEM (HEC-HMS): PHYSICALLY-BASED SIMULATION COMPONENTS

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Abstract The Hydrologic Modeling System (HEC-HMS) was conceived as a software-based tool for simulating the hydrologic cycle in the context of engineering problem solving. Water movements in the cycle relevant to common problems in water resources engineering were included: precipitation, infiltration, surface runoff, baseflow, and open channel flow. The first generation of the software focused on simulating individual storm events. The second generation of the software added new components for infiltration modeling to permit continuous simulation. Snowmelt and potential evapotranspiration components, along with an advanced reservoir component, were added for the third generation. The software is very adaptable because it includes a variety of model choices for each segment of the hydrologic cycle. It has been used in many studies for achieving goals in flood damage reduction, reservoir and system operation, floodplain regulation, environmental restoration, water supply planning, among others.

Current and past software releases mostly utilize simulation components built from conceptual models. These models typically rely on empirical data to make predictions about water movement. Nevertheless, many of these models contain parameters with a physical basis and may be estimated from measurable properties of the watershed. These models can function very effectively when calibration data is available. In the ungaged case, it is generally accepted that physically-based models are a better choice.

Several physically-based simulation components have been included in the software beginning with the very first release. Additional physically-based components were added during the second and third generations. These methods will be summarized including the Green Ampt and Smith-Parlange infiltration components, kinematic wave surface runoff component, and Priestley-Taylor potential evapotranspiration component.

One approach to developing a physically-based model is to use an energy balance. This approach has been used to develop a new snowmelt simulation component. Companion to the snowmelt component are models for direct and diffuse solar shortwave radiation, and downwelling longwave radiation. These models are discussed in detail. The individual model components are also reused for application in a potential evapotranspiration simulation component, and a reservoir evaporation model.

INTRODUCTION

The Hydrologic Modeling System (HEC-HMS) was designed to simulate the rainfall-runoff processes in a wide variety of watershed types. It was anticipated that no single process model would be universally applicable. Therefore it would be necessary to provide process models that could be used in dry climates, humid climates, and climates impacted by snow and ice. Furthermore, more processes of the hydrologic cycle may not be necessary in all applications. For example, snow fall, accumulation, and melt is only necessary in arctic and alpine environments. They may or may not be necessary in temperate climates. Therefore it would be necessary to design a software system where appropriate process models could be selected, including the possibility that certain processes would not be included at all.

The HEC-HMS software was designed in the context of the study process typically used in the U.S. Army Corps of Engineers. Generally the process for a particular project consists of three phases. The first phase is a reconnaissance or screening phase. This phase is typified by the consideration of a number of possible options with study proceeding only far enough to recommend a limited set of options for further study. The second phase is a selection phase. In this second phase the various selected options are framed in concrete terms sufficient to estimate the economic cost and benefit. While the goal is to select the most cost effective option, it is also important to take into proper account the environmental benefits. The final third phase is the complete design of the option selected as the best alternative from an economic and environmental standpoint. It was recognized that only minimal effort can be invested in collecting data and constructing simulation models at the early phase, due to the large number of options under consideration. In the second phase more detailed models should be used in order to develop accurate estimates of economic and environmental variables. The final phase usually must include detailed study in order to have sufficient information to complete a good design. Therefore the HEC-HMS software would need to contain process models that range from simple to detailed. While the simple models would be quick and easy to implement in a screening study, more detailed models would also be included for use in design studies.

Breaking the hydrologic cycle into component parts for representation in HEC-HMS was envisioned as a way to provide process models for use in different climates and with differing levels of data requirements and complexity of use. Each pathway in the hydrologic cycle could then provide several options for the different uses. This approach would also facilitate expanding the modeling choices in the future without requiring radical changes in the simulation framework. The various atmospheric and land surface components of the hydrologic cycle included in the program are: precipitation, evapotranspiration, snowmelt, solar radiation, canopy interception, surface depression storage, infiltration, surface runoff, and baseflow. The atmospheric and land surface components are represented by subbasin elements. Additional hydraulic components include source inflows, channel routing, channel losses, diversion structures, and reservoirs. The hydraulic components are represented by reach elements, diversion elements, junction elements, sink elements, source elements, and reservoir elements.

PHYSICALLY-BASED SIMULATION

One useful definition of a physically-based process model is a model whose parameters can all be directly measured from the watershed. However, beyond the measurement of the parameters it is also implied that the physics of the process are maintained by the model. The physics may be represented through conservation equations such as conservation of mass, conservation of momentum, or conservation of energy. In some cases it may be necessary to conceptualize the physics in order to make the solution tractable or to meet time performance requirements. In these cases it is preferable to maintain as much of the physics as possible, yet making reasonable assumptions to do not unduly impact for overall representation of the physical processes.

One example of a conceptual but physically-based approach to model development comes from water infiltration in soil. Physical properties of soil are heterogeneous and the precipitation that falls on the watershed varies in time and space. The result is that soil across a watershed will have a wide variety of soil water content values, and these values will vary by depth below the surface. It would be tremendously difficult to construct a soil model which characterizes the variation in soil water content across the watershed and with depth. One good conceptualization is to conceptualize the soil as having a single soil water content that is averaged over the depth of the soil profile. Further, to envision a grid over the watershed so that the soil water content is also averaged over each cell in the grid. A mathematical process model can then be used to evolve the initial soil water content at each grid cell according to the precipitation and potential evapotranspiration boundary conditions, and the infiltration process applied to the conceptual soil within the grid cell.

EXISTING PHYSICALLY-BASED COMPONENTS

A number of physically-based components have been included in HEC-HMS for several years. In fact, some of the components have been included in the program since the very first release. Primarily because of increased data requirements compared to relatively simpler methods, these physically-based methods are generally used less often. They may also be used less often because they are less understood by the program users. Several of the existing process models will now be described.

Priestley-Taylor Evapotranspiration The Priestley-Taylor evapotranspiration model is a simplification of the more complex Penman model (Priestley and Taylor, 1972). The primary assumption is that the air moving over the land surface is at equilibrium with water in the shallow soil. Under these conditions the advective effects are minimal and evapotranspiration is dominated by solar radiation. Therefore the model is well-suited for moist, humid environments. It is not suited to arid or semi-arid climates.

The parameters for the Priestley-Taylor evapotranspiration method are limited. The temperature and net solar radiation must be provided. Additionally, a crop coefficient is specified as a time-series. The crop coefficient is multiplied by the potential evapotranspiration to calculate the actual evapotranspiration. The crop coefficient can be used to take into account plant water use during the various portions of the plant life cycle. Finally, the dryness coefficient can be used to adjust the calculations for the soil moisture state.

HEC-HMS includes two different implementations of the Priestley-Taylor method. The first averages the boundary conditions and properties over the whole subbasin, while the second averages over each grid cell within the subbasin. The implementations were originally added to

Version 3.0 with a time-series of solar radiation. Beginning with Version 3.5 it became possible to use any of the available solar radiation options to drive the model.

Green Ampt Infiltration The Green Ampt infiltration model simulates the movement of water from the surface down into the soil column (Mein and Larson, 1973). A key feature of the model is the assumption of uniform initial soil water content in the soil. Secondarily, the water infiltrating into the soil is assumed to bring the soil from the initial condition to perfect saturation. This conceptual assumption is often called the piston assumption. The piston is represented by the saturated water above and the initial water content below. All water enters the soil under the influence of both gravity and capillary potential until the soil is saturated. Subsequent infiltration happens only under the influence of gravity.

The parameters of the Green Ampt model are measurable properties of the soil. The initial condition is the volumetric soil water content at the beginning of the simulation. Also required is the maximum soil water content associated with saturation of the soil. Remaining parameters are the saturated hydraulic conductivity and the wetting front suction. All of these parameters can be measured by subjecting a soil sample to certain laboratory experiments. Some approximations can be made using previous studies that have found strong correlation between the partially subjective soil texture classification and the actual properties. Even though all the parameters can be estimated directly from the properties of the soils in the watershed, it may still be necessary to perform calibration due to the averaging of the soil water content vertically and the chosen spatial scale for horizontal averaging.

HEC-HMS provides two different implementations of the Green Ampt process model implemented according to the methodology of Li, et al. (1976). All versions of the software going back to the original release have included a Green Ampt implementation averaged over a whole subbasin. A recent release added a gridded implementation. This new implementation allows separate parameters for each grid cell in the subbasin, and separate boundary conditions through a gridded precipitation and other atmospheric processes.

Smith Parlange Infiltration The Smith Parlange infiltration model also simulates the movement of water from the surface down into the soil (Smith and Parlange, 1978). Like the Green Ampt model, it is a conceptualization of the actual physical processes. However, it differs because it does not assume a single hydraulic conductivity as is done in the case of the Green Ampt. In this model the hydraulic conductivity is assumed to decrease exponentially from the saturated condition, as is often found in real soils. This means that it is less likely to over estimate the infiltration at early time during a storm event.

The parameters of the Smith Parlange model include the initial soil water content, the saturated soil water content, and the residual water content. The first two are defined the same as in the Green Ampt model. The residual water content is the water content that will remain after the saturated soil has been allowed to drain and dry for a very long time. The bubbling pressure is a physically-measureable property of the unsaturated soil to pull water into the soil through a suction generated by capillary forces. The conductivity is the rate at which gravity alone forces water through the soil when it is effectively saturated. The pore distribution is a measure of the variation in the size of the void spaces in the soil.

The Smith Parlange model also includes the ability to adjust the infiltration process according to the temperature. Temperature affects the viscosity of the water and the density of the water. These primary effects reduce the total gradient in the soil, which affects the conductivity and the matric potential. These effects were determined through theoretical analysis of the infiltration process and incorporated into the Smith Parlange model. The temperature effects are intended to improve simulation results in desert climates where the properties of water may be significantly different from the properties assumed at standard temperature, as used in virtually all infiltration models.

HEC-HMS provides a single implementation of the Smith Parlange model (Smith, 2002). The implementation assumes that boundary conditions and parameters are averaged over the whole subbasin. The implementation has been included in the program since Version 3.1.

Kinematic Wave Surface Runoff The kinematic wave model is used to simulate the runoff of excess precipitation over the land surface. The model implemented in HEC-HMS is especially well-suited to watersheds with a mixture of pervious and impervious land surface in an urban environment (MacArthur and DeVries, 1993). Typical pervious land use would be landscaped areas covered with grass. The mostly likely impervious land use would be building roof tops and hardscaping such as driveways and sidewalks. The watershed is conceptualized as a pervious and an impervious flow plane, with a percentage of the watershed assigned to each type on the basis of land uses present. The runoff from the flow planes is collected in a small channel that usually represents street gutters. The flow from gutters treated as lateral inflow to a collector channel that usually represents a small storm channel. The flow from the collectors is treated as lateral inflow to a main channel that may be in a natural condition or engineered with concrete bottom and sides.

The geometric parameters for the flow planes are the length and slope of the pervious and impervious planes. The surface roughness is comes from the use of the kinematic wave flow equation, and can be estimated accurately from extensive laboratory and hillslope studies. The percentage of each type of land use in the watershed can be measured from aerial photography of the watershed, or detailed land use mapping.

The parameters of all three channels are similar since the kinematic wave channel flow model is used in all three instances. The geometric parameters include the length and slope of the channel, the Manning's n value for roughness, and the cross section properties. It is also necessary to estimate the typical contributing area for street gutters when they empty into the collector. Likewise it is necessary to estimate the average contributing area for collector channels that empty into the main channel.

The kinematic wave transform model has been a feature of the program since the first release.

NEW PHYSICALLY-BASED COMPONENTS

Several new physically-based components have recently been added to the program. Previously the solar radiation was entered by the user as a time-series of values or as a time-series of grids.

This required the actual solar radiation values to be calculated with an external model. Adding a solar radiation component directly in HEC-HMS allows better integration of solar radiation in various places of the hydrologic cycle where it exerts an influence. An energy-balance snowmelt model has also been added. Previously the snowmelt simulation was performed with a detailed temperature-index model. The new energy-balance model can provide additional flexibility not found when only temperature is used.

Energy-Balance Snowmelt Component The energy-balance concept can be an effective way to determine the melting of an accumulated snowpack. The primary source of energy to the snowpack is solar radiation, including both direct and diffuse radiation. Other sources of energy to the snowpack include downwelling longwave radiation, latent flux due to moist air condensing in the snowpack and releasing heat energy, and sensible flux due to heat exchanges between the snowpack and atmosphere via conduction. In some cases there may also be a flux of heat energy from the ground into the snowpack via conduction. The implemented approach follows Tarboton, et al. (1995) with modifications suggested by Luce (2000) and You (2004).

Most of the parameters to the energy-balance snowmelt component are in fact the atmospheric boundary conditions. It is required to have the air temperature, air pressure, relative humidity, wind speed, total solar shortwave radiation, and downwelling longwave radiation. The only other parameter is the discrimination temperature for determining if the precipitation is liquid or frozen based on the air temperature. Quasi-parameters, such as the snowpack albedo, are calculated using robust equations found in the literature.

HEC-HMS includes two different implementations of the energy-balance snowmelt method. The first averages the boundary conditions and properties over the whole subbasin, while the second averages over each grid cell within the subbasin. Both implementations were added to Version 3.5.

Shapiro Solar Radiation Component Several simulation components in HEC-HMS require solar radiation as a boundary condition. The Priestley-Taylor evapotranspiration method requires the net solar radiation, considering direct and indirect incoming radiation as well as radiation reflected at the land surface. The new energy-balance snowmelt component also requires the total incoming solar radiation in order to perform an energy balance at the snow surface, where dynamic albedo is considered for the reflection component. An explicit representation of solar radiation, beyond an external time-series, is a new feature in the software.

The Shapiro model (Shapiro, 1987) begins with the incoming solar radiation at the top of the atmosphere, taking into account the location on Earth and the day of the year. The radiation is then reduced by the presence of clouds. Clouds are considered at high, middle, and low elevation. Clouds can reflect radiation upward and also attenuate radiation as it passes downward through the cloud. The amount of reflection and attenuation is determined by the type of cloud and also the density. The calculations are repeated for the clouds at all three levels. In general the data necessary to satisfy the model is only available at regional and international airports where the METAR data feed is produced.

HEC-HMS includes two different implementations of the Shapiro solar radiation method. The first averages the boundary conditions and properties over the whole subbasin, while the second averages over each grid cell within the subbasin. Both implementations were added to Version 3.5.

CONCLUSIONS

Physically-based simulation components can be a powerful tool for watershed hydrology simulation. They have the advantage of parameters that can generally be measured or directly estimated from properties of the watershed. However, they typically require more boundary condition information (temperature, solar radiation, atmospheric pressure, other meteorological data) that models that are more conceptual in nature. Nevertheless, the closeness of the model representation to the observable physical process builds confidence during the modeling process.

HEC-HMS has included some physically-based components since the very first release. Additional physically-based components have been added in past years and recently. Additional components will also be added in the future. The applicability and range of HEC-HMS will thus continue to increase through the use of physically-based modeling components.

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